TITLE: Development of X-33/X-34 Aerothermodynamic Data Bases: Lessons Learned and Future Enhancements

TITLE: Aerodynamic Design and Optimisation of Flight Vehicles in a Concurrent Multi-Disciplinary Environment [la Conception et l'optimisation aerodynamiques des vehicules aeriens dans un environnement pluridisciplinaire et simultane]

Development of X-33/X-34 Aerothermodynamic Data Bases: Lessons Learned and Future Enhancements

(October 1999)

C. G. Miller
NASA Langley Research Center
Mail Stop 408A
Hampton, VA 23681-2199
USA

Summary: A synoptic of programmatic and technical lessons learned in the development of aerothermodynamic data bases for the X-33 and X-34 programs is presented in general terms and from the perspective of the NASA Langley Research Center Aerothermodynamics Branch. The format used is that of the "aerothermodynamic chain," the links of which are personnel, facilities, models/test articles, instrumentation, test techniques, and computational fluid dynamics (CFD). Because the aerodynamic data bases upon which the X-33 and X-34 vehicles will fly are almost exclusively from wind tunnel testing, as opposed to CFD, the primary focus of the lessons learned is on ground-based testing. The period corresponding to the development of X-33 and X-34 aerothermodynamic data bases was challenging, since a number of other such programs (e.g., X-38, X-43) competed for resources at a time of downsizing of personnel, facilities, etc., outsourcing, and role changes as NASA Centers served as subcontractors to industry. The impact of this changing environment is embedded in the lessons learned. From a technical perspective, the relatively long times to design and fabricate metallic force and moment models, delays in delivery of models, and a lack of quality assurance to determine the fidelity of model outer mold lines (OML) prior to wind tunnel testing had a major negative impact on the programs. On the positive side, the application of phosphor thermography to obtain global, quantitative heating distributions on rapidly fabricated ceramic models revolutionized the aerothermodynamic optimization of vehicle OMLs, control surfaces, etc. Vehicle designers were provided with aeroheating information prior to, or in conjunction with, aerodynamic information early in the program, thereby allowing trades to be made with both sets of input; in the past only aerodynamic data were available as input. Programmatically, failure to include transonic aerodynamic wind tunnel tests early in the assessment phase led to delays in the optimization phase, as OMLs required modification to provide adequate transonic aerodynamic performance without sacrificing subsonic and hypersonic performance. Funding schedules for industry, based on technical milestones, also presented challenges to aerothermodynamicists seeking optimum flying characteristics across the subsonic to hypersonic speed regimes and minimum aeroheating. This paper is concluded with a brief discussion of enhancements in ground-based testing/CFD capabilities necessary to partially/fully satisfy future requirements.

Introduction: Aerothermodynamics, defined herein as encompassing aerodynamics, aeroheating, and fluid dynamics and physical processes, is the genesis for the design, development, and flight of space transportation vehicles and is in the critical path to success for such vehicles. The aerothermodynamic challenge is to provide the optimum design (i.e., outer mold lines (OML)) to safely satisfy mission requirements including abort scenarios and to reduce design conservatism, risk, and cost; i.e., the optimum flying vehicle with minimum structural (i.e., surface pressure/shear) and heating loads, translating into reduced weight and reduced operation costs. Aerothermodynamics provides crucial information to other key disciplines such as structures, materials, including thermal protection systems (TPS), avionics, guidance, navigation and control, propulsion, etc. The three sources of aerothermodynamic information are: (1) ground-based facilities, (2) computational fluid dynamics (CFD) and/or engineering computer codes, and (3) flight experiments.

In recent years, large volumes of aerothermodynamic information have been generated at the NASA Langley Research Center (LaRC), both experimentally and computationally, in support of high-priority, fast-paced programs such as the RLV/X-33 Phase I and X-34 programs initiated in April 1995, followed a year later by X-33 Phase II, X-34 (second phase), X-38, X-43 (Hyper-X), Missions from Planet Earth (i.e., planetary exploration and Earth sample return missions), and most recently, X-37. These studies, collectively, challenged Langley's aerothermodynamic capabilities/resources. As to be expected, the work environment changed significantly due to the abrupt increase in generation of aerothermodynamic information for external customers. Demands on experimental aerothermodynamicists were especially large since the LaRC Aerothermodynamic Facilities Complex (AFC) (**Micol, 1998**), comprised of five conventional-type, blowdown-to-vacuum hypersonic wind tunnels, represents the Agency's sole source of experimental, ground-based hypersonic aerodynamic and aeroheating data. Downsizing of personnel also occurred in this period, corresponding to experienced aerothermodynamicists and facility technicians who retired, transferred, etc., generally not being replaced, and outsourcing impacted key areas of the aerothermodynamic infrastructure (**Miller, 1998**). Another change to the work environment was due to programs such as X-33 (primarily schedule driven) and X-34 (primarily cost driven) being industry led as opposed to NASA led. Schedules/milestones

Paper presented at the RTO AVT Symposium on "Aerodynamic Design and Optimisation of Flight Vehicles in a Concurrent Multi-Disciplinary Environment", held in Ottawa, Canada, 18-21 October 1999, and published in RTO MP-35.

established by customers failed to take full advantage of experimental and/or computational aerothermodynamic capabilities or, at the other extreme, were unrealistic in expectations. To satisfy customer milestones, which were often driven more by programmatic considerations (e.g., funding schedules) than technical issues, AFC wind tunnels were operated in a "production-like" manner, running extended/double shifts and weekends.

A review of aerothermodynamic capabilities at the NASA LaRC is provided by **Miller, 1998**. This review includes: (1) the highly iterative aerothermodynamic process for screening initial aerospace vehicle concepts, optimization of aerolines via parametric studies, and benchmark data for final design and establishment of the flight data book (**Fig. 1**); (2) aerothermodynamic methodology which translates to the synergism between ground-based testing and CFD predictions throughout entry into the Earth's atmosphere (**Figs. 2 and 3**); and (3) the resources/infrastructure required to provide accurate/credible aerothermodynamic information in a timely manner. Impacts on Langley's aerothermodynamic capabilities due to programmatic changes, downsizing, outsourcing, etc., are discussed in this review, as are sample applications of these capabilities to the X-33, X-34, X-38, and X-43 programs along with some lessons learned.

The primary purpose of the present paper is to expand upon the lessons learned presented previously by **Miller, 1998** for X-33 and X-34. Programmatic and technical lessons learned from these two programs will be presented in a general manner and will not be identified with a specific program. Many, if not most, of these lessons learned are well known and documented within the aerothermodynamic community. The present synoptic of lessons learned may prove useful for new members of the aerothermodynamic community and to engineers/scientists in other disciplines who are users of aerothermodynamic information, and may serve as a guide/reminder for future programs requiring extensive aerothermodynamic information. These lessons learned are from the perspective of the Aerothermodynamics Branch (AB) of the LaRC, which served as a subcontractor to industry via formal task agreements. (For the convenience of readers, recent publications by the Aerothermodynamics Branch on X-33 and X-34 are given in the "**References.**")

Lessons Learned:

Preface: The aerodynamic data bases upon which the X-33 and the X-34 will fly (i.e., the aerodynamic flight data books) are essentially exclusively from wind tunnel testing. Relatively comprehensive aerodynamic data bases across the subsonic through hypersonic speed regimes were generated for both programs via testing in a number of wind tunnels at the LaRC (e.g., Low Turbulence Pressure Tunnel (LTPT), 14- by 22-Foot Subsonic Tunnel, 16-Foot Transonic Tunnel, Unitary Plan Wind Tunnel (UPWT) Legs 1 and 2, and the hypersonic wind tunnels of the AFC), the NASA Marshall Space Flight Center (MSFC) 14- by 14-Inch Trisonic Wind Tunnel, and several industry subsonic-to-supersonic wind tunnels. The role of CFD in the generation of X-33 and X-34 aerodynamic data bases was complementary in nature. There are two primary reasons for the dominance of wind tunnel testing over CFD for these programs. Once models and associated hardware are available, wind tunnels provide huge quantities of aerodynamic performance information over wide ranges of attitude (alpha, beta), control surface deflections, individually and in combination, and flow conditions in a relatively short period of time and with a high degree of credibility based on decades of previous experience. The second reason is available wind tunnels cover the flight regimes for the X-33 and X-34 nicely, in that the maximum flight Mach number for X-33 is expected to be around 10 and to be around 7 for the X-34. As observed from **Figs. 2 and 3**, the contribution of CFD increases significantly above Mach 10, or so, where reacting flowfields influence aerodynamic characteristics. In the generation of aeroheating data bases, CFD was an equal and synergistic partner with wind tunnel testing. Because of the major role played by wind tunnels in establishing aerothermodynamic data bases for X-33 and X-34, a significant portion of the subsequent lessons learned are associated with ground-based testing.

Lessons learned presented in this section are loosely organized based on the "aerothermodynamic chain" of **Miller, 1998 (Fig. 4)**. The links of this chain are personnel, facilities, models/test articles, instrumentation, testing techniques, and CFD. These links are universal to all aerothermodynamic activities and, again, are viewed herein from an Aerothermodynamics Branch perspective. No attempt has been made to prioritize the following lessons learned, nor to separate programmatic lessons learned from technical ones. Where deemed appropriate, recommendations are provided which are subjective and may not be universally applicable.

Personnel: To ensure a successful program from the viewpoint of flyability and survivability, it is imperative that certain groups work closely together as a true team:

(1) Experienced, senior aerothermodynamicists who have worked similar programs (e.g., Shuttle Orbiter) should be blended with junior aerothermodynamicists who have not yet learned what is impossible and are eager to learn and to try new approaches, etc. The advantages provided by such a blending have been demonstrated in numerous programs, yet this approach is not always utilized.

(2) Aerothermodynamicists and systems analysis engineers responsible for the initial vehicle concept, for applying engineering codes and interpolation procedures to populate the aerodynamic and aeroheating data bases, and for generating flight trajectories should work closely together from the beginning to the end of the program. Experienced aerothermodynamicists often will identify

deficiencies in initial concepts, thereby allowing system analysis engineers to iterate on the concept prior to its entering the aerothermodynamic process (**Fig. 1**), specifically screening and optimization. Such an exchange can save considerable time and resources. Systems analysis engineers should be involved in the development of wind tunnel test matrices and decisions relative to the output of data reduction procedures. Personnel working guidance, navigation and control (GN&C) issues should also be brought into the aerothermodynamic process early, as they are the ultimate customer for aerodynamic measurements and predictions. Likewise, designers of the thermal protection system (TPS), who are customers for aeroheating measurements and predictions, should be included.

(3) It is imperative that experimental and computational aerothermodynamicists work together from the beginning to the end of the program. The ultimate creditability of aerodynamic and aeroheating information is achieved when independently performed wind tunnel measurements and CFD predictions for wind tunnel cases are compared and found to be in excellent agreement over a range of attitude and flow conditions. Wind tunnel measurements and CFD predictions are highly complementary and together provide accurate aerothermodynamic information throughout the flight trajectory; i.e., across the subsonic to hypersonic regimes. There is a tendency of computationalists to bypass comparing CFD predictions to wind tunnel measurements and to apply CFD only to flight conditions. This bypass should be avoided for reasons discussed previously. In one of the subject programs, an aerothermodynamicist capable of performing both high level experimental work and high level computational (via CFD) work proved to be extremely valuable. Knowledge of the strengths and weaknesses of both disciplines allowed the strengths to be systematically combined and optimized. This demonstration of the advantages provided by an individual having combined experimental and computational skills/capabilities has led to the ongoing development of additional aerothermodynamicists with both skills.

(4) It is important to have experimental and computational aerothermodynamicists working aerodynamic issues and those working aeroheating issues establish strong lines of communication. Often, "anomalies" observed in aerodynamic force and moment measurements can be explained by the detailed surface information achieved in experimental aeroheating studies. Detailed studies of shock-shock interactions, flow separation-reattachment phenomena, boundary layer transitions, etc., via aeroheating measurements are beneficial to aerodynamicists in explaining force and moment trends. Naturally, inputs from computationalists who generate detailed surface and flowfield information are extremely valuable in this process. Working aerodynamic and aeroheating issues together, OMLs may be varied to both enhance the aerodynamic performance and to minimize aeroheating levels.

(5) The same team of experimental aerodynamicists should test across the subsonic-to-hypersonic speed regimes, as opposed to different teams testing at subsonic, transonic, supersonic, and hypersonic conditions. The continuity and flexibility provided by a single team testing across the speed regimes is believed to outweigh the collective outputs of specialists in each regime that must be coordinated and assembled into one story.

Facilities: Typically, initial aerodynamic screening or assessment is performed in relatively low-cost, low-performance subsonic tunnels and using rapidly fabricated, inexpensive stereolithography (SLA) resin models in the unheated flow of the LaRC 22-Inch Mach 15/20 Helium Tunnel. Configuration OMLs are modified/varied in an iterative manner to provide acceptable hypersonic aerodynamic performance, generally at relatively high angles of attack, and subsonic approach and landing characteristics. Vehicle designers may be approaching closure on OMLs via this approach before testing at transonic conditions reveal significant aerodynamic performance problems. It is imperative for most all aerospace vehicle concepts that transonic aerodynamic information be obtained early in the program, such that subsonic, transonic, and hypersonic information is used concurrently in the optimization of OMLs to achieve desired flying characteristics across the entire speed regime, from high altitude hypersonic conditions to approach and landing.

In most cases, the credibility of the experimental aerodynamic data base is enhanced considerably with the simulation of flight values of Reynolds number based on appropriate full-scale vehicle dimensions. Generally, existing hypersonic wind tunnels within NASA and the United States Air Force simulate flight values of Reynolds number, for a given Mach number, and provide a sufficient Reynolds number range to produce fully laminar and equilibrium turbulent boundary layer/shear layer flow about the test article (**Miller, 1998**). However, the simulation of flight Reynolds numbers at subsonic, transonic, and low supersonic conditions is a formidable task and can be accomplished in relatively few facilities. One is the NASA National Transonic Facility (NTF) through the use of cryogenic nitrogen for the test medium. Stringent model design and fabrication requirements and facility operation costs make tests in the NTF relatively expensive and require a long lead time. The vehicle designer is confronted with a trade of reduced risk for increased time and money. As a minimum, limited tests at transonic flight values of Reynolds number on the baseline configuration are recommended to determine if the major portion of the subsonic-to-supersonic aerodynamic data base obtained at lower than flight values of Reynolds number is credible.

An alternative approach is to apply CFD to wind tunnel conditions corresponding to relatively low values of Reynolds number; and, if prediction compares well with measured aerodynamic forces and moments, apply CFD to flight values of Reynolds number to determine the aerodynamic performance. Thus, subsonic-to-low supersonic wind tunnel testing at flight values of Reynolds number or the use of CFD to extend wind tunnel conditions to flight should be used to decrease the risk level associated with the development of the aerodynamic flight data book.

In high-priority, fast-paced programs involving testing in numerous facilities to achieve a wide range of flow conditions, there is a tendency to accept facility performance without questioning nor understanding facility and associated instrumentation limitations. For example, in the case of hypersonic wind tunnels, radial and axial flow uniformity, partial flow blockage phenomena, flow particulate levels, vibrational excitation and possible departure from equilibrium, flow liquefaction, free-stream disturbance level due to particulates but primarily due to acoustic disturbances radiated from the nozzle wall boundary layer, etc., are all factors that must be understood to enhance the data credibility. It is imperative that experimental aerodynamicists, within Government and industry, understand facility and instrumentation limitations and the corresponding influences on data accuracy.

On several occasions, significant delays occurred in the reduction of data acquired in wind tunnel tests to the required form. In some cases, data transfer mechanisms/procedures between wind tunnels and customers were not compatible. Potential incompatibilities related to data transmission and receiving need to be addressed upfront and early in the planning process. Careful planning and coordination are required by experimental aerothermodynamicists to minimize/eliminate delays in data reduction.

Conflicts that occur because of competition among concurrent programs for resources such as facility occupancy, model design/fabrication, etc., are generally resolved through negotiations and compromise. In most cases, major milestones are built around freezing of OMLs, which in turn depends on testing in specific facilities at specific times. When two or more major programs request the same resources for the same time, it is important that clearly defined priorities be established by the appropriate level at the host laboratory and be provided to all involved workers to minimize confusion and dysfunctionality.

Models: The major contributor to the failure to meet wind tunnel schedules and the corresponding milestones for delivery of aerodynamic data was delays in design and fabrication of metallic force and moment models (**Fig. 5**). In Phase I of the X-33 program involving the aerodynamic assessment and optimization of three industry concepts in parallel with the X-34, all models tested in these fast-paced programs were fabricated in-house at the LaRC and were delivered on time and within cost. This success was achieved by assigning a high priority to the X-33 and X-34 programs and the Fabrication Division operating numerical cutting machines 24-hours per day and 7 days per week. Modifications to model components to enhance aerodynamic performance were generally performed in a day or two, and often overnight. Metallic model fabrication began to be outsourced about the time that Phase II of the X-33 program was initiated. The impact of model delivery delays and the testing of models without verification of the accuracy of OMLs due to insufficient time was substantial. The time associated with fabrication of metallic models represents the major contributor to the total time to perform an experimental aerodynamic test in a wind tunnel (**Fig. 6**).

In an attempt to more rapidly obtain hypersonic aerodynamic data, ceramic force and moment models were made and tested. Ceramic models can be made in about an order of magnitude less time than stainless steel models. Although not a total success, due primarily to the lack of surface fidelity in critical aerodynamic surfaces, lack of precise determination of transfer distances, and challenges associated with precision alignment of the strain-gauge balances, preliminary findings were nevertheless encouraging. High temperature resin SLA models of the X-34 were also tested in heated hypersonic wind tunnels, again with partial success. Stainless steel continues to be the material of choice for precision force and moment models benchmark tested in the heated hypersonic wind tunnels of the AFC. Attempts to refine/enhance fabrication of ceramic and high-temperature resin force and moment models will continue in an effort to reduce the time to generate hypersonic aerodynamic information for assessment/optimization phases of the aerothermodynamic process; i.e., reduce design cycle time.

On the positive side, significant advances were made in the fabrication of precision ceramic models for aeroheating studies. One example is scaling of metallic TPS panels to simulate the bowing that will occur in the hypersonic portion of the X-33 flight trajectory (**Horvath et al., 1999**). These high fidelity models were made and tested to determine the influence of surface roughness due to panel bowing on boundary layer transition.

Instrumentation: Protecting strain-gauge balances from adverse thermal gradients during a run in the heated flow of a hypersonic wind tunnel, or accurately compensating for such gradients proved to be quite challenging. Although the balances were water cooled, heat conduction through the stainless steel walls of the model and/or along the sting/blade support and into the balance compromised accuracy. In both the LaRC 20-Inch Mach 6 Air and 31-Inch Mach 10 Air Tunnels, the force and moment models were pitched-paused and exposed to the flow from one to three minutes. Heat conduction along the sting or through the blade mount was reduced by water cooling. Balances were not actively compensated

for temperature gradients and were passively compensated only for two temperatures, namely room temperature and a temperature higher than this valve. The relatively small models offered little heat sink capacity. Minimizing the contact surface of the balance with the model provided the best protection against unacceptable temperature gradients and proved successful in most cases. Credible aerodynamic data was obtained, but only after many repeat runs, comparison of runs for which the angle of attack was increased with run time to those where alpha was decreased, soak runs where alpha was held constant for the entire run, and so forth. Needed is a fully temperature compensated strain-gauge balance and/or improved methods for balance cooling or protection of the balance from heat conduction.

On at least one occasion, differences between experimental measurements and computational predictions were attributed primarily to uncertainties in the model attitude (i.e., alpha and beta). Uncertainties in the model attitude, which is generally measured with conventional inclinometers for a no-flow case, contributed to corresponding uncertainties in aerodynamic and aeroheating trends and levels and resulted in several repeat runs having to be made. Needed is a user friendly, nonintrusive, precision method to measure model alpha and particularly beta in real time during a tunnel run (i.e., flow-on condition).

On the positive side, the Langley developed phosphor thermography technique (**Fig. 7**) was heavily utilized for the X-33, X-34, and a number of other programs and performed in an outstanding manner. This technique for measuring global, quantitative aeroheating distributions on models truly revolutionized the aerothermodynamic process and is indeed "better, faster, cheaper" than previously used techniques. (Details and capabilities of this technique are discussed by **Merski, 1999**.) One new capability with this technique is to extrapolate heating distributions measured on a model in a hypersonic wind tunnel to flight values of vehicle surface temperature (**Fig. 8**), and to do so immediately following a tunnel run. The accuracy of this extrapolation of ground-based data to flight has been substantiated with comparisons to CFD predictions for both wind tunnel conditions and flight conditions for the X-34 (**Merski, 1999**).

Testing Techniques and Procedures: All force and moment models, including those for benchmark studies, should be designed and fabricated for configuration buildup (i.e., each component attached to the basic body or fuselage may be removed and replaced with a section contoured to the basic body) as opposed to being fabricated in one piece. Models with configuration buildup capability are, naturally, required in the assessment and optimization phases of the aerothermodynamic process and should also be employed in the benchmark phase. "Theoretically OMLs are frozen prior to entering the benchmark phase in the current environment of reduced design time; but, the reality is that the OMLs generally continue to change well into benchmarking. Configuration buildup capability allows OML changes to be more rapidly and less expensively incorporated into the model, and also contributes to addressing concerns when/if measured aerodynamic data does not follow intuition. Such a situation occurred during benchmarking of hypersonic aerodynamic performance for the X-33, whereby the forces and moments associated with body only were quickly measured and each set of components (i.e., fins, flaps, tails) added one at a time to deduce the contribution to aerodynamic characteristics (**Murphy et al., 1999**; see **Fig. 9**). Testing the same model (and strain-gauge balance(s)) in multiple hypersonic wind tunnels providing a range of normal-shock density ratio from 4 to 12 (i.e., range of ratio of specific heats within the shocklayer of the model from 1.15 to 1.67) (**Fig. 10**) provides aerodynamicists with additional insight as to the cause and effect of both geometric and flow variables.

Other than discrete surface pressure measurements made on models in support of flush air data system (FADS) development and a 0.03 scale X-33 pressure model tested in the LaRC 16-Foot Transonic Tunnel by engineers working structures problems, very few pressure measurements were performed in wind tunnels for the X-33 and X-34 programs. One reason for the dearth of pressure measurements is conventional pressure models using electronically scanned pressure (ESP) systems require a relatively long time to fabricate and are correspondingly expensive; also, lengthy setups and checkouts/shakedowns are generally required for such models. Situations did occur in the X-33 and X-34 programs when aerothermodynamicists would have benefited significantly from measured pressure distributions, particularly in comparisons of CFD predicted aerodynamic coefficients with measured values and in resolving anomalous trends or levels in these coefficients. If successfully developed and applied, nonintrusive, optical-video based, global surface pressure measurement techniques for heated and unheated wind tunnels should be utilized in future studies similar to X-33 and X-34. These techniques will be faster, better, and cheaper than conventional ESP systems and provide detailed information in critical areas on the model; e.g., in regions of shock-shock interaction, flow separation-reattachment (including the entire leeward surface), etc.

Hypersonic boundary layer transition from laminar to turbulent during descent from suborbit or orbit typically results in an increase in heating to the windward surface of the vehicle by a factor of 3 to 5. Thus, a reasonably accurate determination of flight conditions where boundary layer transition occurs is essential for most aerospace vehicles to ensure that aeroheating levels and loads remain within TPS design limits. Ideally, such information would be incorporated into the design of the TPS, including material selection, split line definition, and material thickness. Although progress has been made in developing computational techniques for predicting hypersonic boundary layer transition onset, aerothermodynamicists still rely primarily on semi-empirical methods used for the Shuttle Orbiter and other vehicles. However, these methods today enjoy the

capabilities provided by advances in computers and by the phosphor thermography technique. Accurate determination of boundary layer transition on hypersonic wind tunnel models with and without discrete trip elements over a wide range of attitude and flow conditions (primarily Reynolds number) is possible with the thermography technique. This information can be obtained quickly and inexpensively. For the X-33 program, Langley attempted to develop a boundary layer transition criteria applicable to flight. Approximately 275 runs were performed in the Langley 20-Inch Mach 6 Tunnel over a wide range of Reynolds number with ceramic aeroheating models having different discrete trip arrangements. Inviscid flowfield solutions coupled with boundary layer solutions (**Hamilton et al., 1998**) provided local conditions of interest about the model, specifically boundary layer thickness, edge Mach number, and Reynolds number based on momentum thickness at the location of the surface disturbance(s). The wind tunnel results in terms of these local flow properties were observed to correlate nicely (**Berry et al., 1999;** see **Fig. 11(a)**) and allowed a region in terms of altitude, velocity, and angle-of-attack to be predicted for which the boundary layer would be laminar at altitudes above this region, and turbulent below it (**Thompson et al., 1998;** see **Fig. 11(b)**). This boundary layer transition criteria for the X-33 has proven to be extremely valuable in tailoring trajectories so to not exceed limits on the metallic TPS yet satisfy mission requirements. The accuracy of this approach will be determined by the first flights of the X-33. If proven accurate, as expected, this approach is recommended for all aerospace vehicles expected to experience boundary layer transition near the region of peak heating during descent, and should be performed as early in the program as appropriate. (A major concern with this approach is the measurement of transition onset in a conventional-type hypersonic wind tunnel for which the freestream flow is acoustically contaminated. Freestream disturbances are expected to promote early transition on the model, hence the findings as applied to flight should be conservative. It is primarily because of these acoustic disturbances in the freestream of the wind tunnel, which result from the turbulent boundary layer on the nozzle wall, that flight measurements of transition onset are needed to substantiate this approach.)

Because of the long lead time in the design and fabrication of a force and moment model or pressure model with jets at various locations to simulate reaction control system (RCS) interactions by blowing of various gases, this important phase of the aerothermodynamic study should be initiated just prior to or immediately following the freezing of OMLs. The RCS jets should be calibrated in a vacuum chamber, model setup and shakedown is generally laborious, and there is little room for error with the flow-through five-component strain-gauge balance. Another challenge associated with RCS testing is that the effect of the RCS interaction to be measured is often on the same order of, or smaller than, the balance accuracy (as the balance must be sized for full scale model loads), or the thermal drift. The test matrix is quite large due to the number of variables involved, hence tunnel occupancy time is substantial, and data reduction and incorporation into the flight aerodynamic data book may not be straightforward. The RCS data will enrich the aerodynamic data base via comparisons of forces and moments without blowing to those obtained with the benchmark force and moment model. An effort should be made to include diagnostics that provide insight as to the characteristics of the flow, including state of the boundary layer, approaching the jet and downstream of the jet (e.g., surface streamline patterns via oil flow, surface temperature via infrared emission, focused schlieren, etc.). Complementary CFD predictions for RCS plume, vehicle flowfield, and possibly vehicle surface interactions should be performed. The upcoming comparisons of X-33 flight results with an active RCS to CFD predictions and to wind tunnel data, including the methods used to extrapolate ground-based data to flight, should be of tremendous benefit to the aerothermodynamic community.

In the haste of performing high-priority, fast-paced aerothermodynamic studies, the general tendency is to omit complementary diagnostics to the force and moment tests and thus lose a valuable tool for explaining trends in the data that may be unexpected. Complementary diagnostics such as oil flow (**Fig. 12**), schlieren, infrared emissions, etc., should be employed whenever feasible. As noted previously, it is very beneficial for experimentalists and computationalists performing aerodynamic studies and for colleagues performing aeroheating studies to interact with one another to obtain a thorough understanding of flow characteristics (e.g., boundary layer/shear layer transition, shock-shock and shock-boundary layer interactions, flow separation and reattachment, sonic line location, etc.) about the complete vehicle.

Computational Fluid Dynamics (CFD): CFD contributed significantly to the development of aeroheating data bases for X-33 and X-34, addressed specific, localized phenomena such as shear layer impingement on the X-33 engine modules, and played a complementary role in the development of aerodynamic data bases which required full tip-to-tail solutions. Through these applications to complex configurations over wide ranges of flow conditions and attitudes, CFD capabilities increased considerably as codes were modified to enhance accuracy, increase speed, and provide new capabilities such as RCS interactions, full wake solutions, etc. Extensive comparisons were performed between the two primary Navier-Stokes solvers for hypersonic flows used within NASA, namely the Langley developed LAURA code and the commercially available GASP code from Aerosoft, Inc., in which strengths and weaknesses were identified. (See, for example, **Fig. 13**.) Efficiency and effectiveness of surface and volume grid generation were enhanced, although generation of these grids remained the major portion of the total time to generate a solution (**Fig. 14**). Advantage was taken of massive parallelization techniques to significantly reduce the running time

required for LAURA. Most importantly, confidence in using CFD to provide aerodynamic and aeroheating data for aerospace vehicles was increased appreciably by comparisons of CFD predictions to wind tunnel measurements and code to code. These comparisons provided a better understanding of what physical and numerical models to use (**Hollis et al., 1999;** see **Fig. 15**) in future applications.

From X-33 and X-34 experiences in aerothermodynamics, it is strongly recommended that computational and experimental aerothermodynamicists work together in the development of both aerodynamic and aeroheating data bases. The strengths of CFD and ground-based testing are complementary and, used together, provide a better product. Due to expected advances in CFD in the future, particularly in reduced times required to run full Navier-Stokes solvers tip-to-tail, and to dedicated computers for a given program, the time will come when CFD plays a dominant role in the development of aerothermodynamic data bases. However, for the next decade, it is believed that vehicle designers will rely primarily on wind tunnels for subsonic-to-low-hypersonic (i.e., Mach 0.1 to 10) aerothermodynamic information and on CFD predictions for hypersonic-hypervelocity flows (i.e., Mach numbers in excess of 10, or so).

Future Enhancements: Plans to advance aerothermodynamic capabilities at the NASA Langley Research Center in the future will not become reality without adequate resources in terms of personnel (i.e., expertise/competency), equipment and sources of relatively long-term (3 to 5 years) funding. Within the present resources of the Aerothermodynamics Branch, several enhancements have been, or are in the process of being, initiated. For the sake of brevity, example enhancements will only be mentioned briefly; additional information on enhancements is provided by **Miller, 1998**.

The emphasis on future enhancements is to provide aerothermodynamic information faster (**Fig. 16**) for all phases of the aerothermodynamic process; i.e., development of initial concepts, assessment, optimization, and benchmarking. Factors in computational and experimental aerothermodynamics that now require relatively long periods of time to perform are being worked on an effort to reduce time. Computationally, an ambitious effort is underway to develop an unstructured hypersonic viscous solver having all the capabilities of the benchmark Langley LAURA code but with a reduction in the total time to generate grids and obtain a full viscous, tip-to-tail solution by an order of magnitude or more. Until such time this unstructured solver is operational, the optimization of the LAURA code for massive parallel processing on nonvector machines will continue. Significant advances have been made in reducing the time required to generate structured surface/volume grids and work is in progress to further achieve an order of magnitude reduction in time. An unstructured version of the Langley LATCH (boundary layer solver) code (**Hamilton et al., 1998**) has been developed and coupled with the FELISA code, an unstructured inviscid solver. This combination of FELISA and UNLATCH (UNstructured LATCH) will greatly accelerate the development of comprehensive aeroheating data bases for the windward surfaces of vehicles. This combination is also an important ingredient to a process recently developed to rapidly predict peak heating and heating loads for a given trajectory and "automatically" select optimum TPS materials, determine split lines between different TPS materials, and size the TPS.

Additional computational plans include the continued development and validation of advanced turbulence models for hypersonic flows; enhancement of jet plume-flowfield-surface interaction (i.e., reaction control system) capabilities; possible revival of equilibrium radiation codes to address aerothermodynamic issues associated with very high velocity return to Earth missions; continued advancements in DSMC by coupling to continuum Navier-Stokes solvers to predict RCS phenomena in the rarefied flow regime and extension of DSMC capabilities lower into the atmosphere; the exploiting of boundary-layer theory and triple-deck theory to compute the effects of global and local changes to surface catalysis on computed heating rates; and development of laminar wall function approximation to help reduce grid requirements and accelerate convergence of CFD solutions for hypersonic, viscous flow.

A strong emphasis has been placed on obtaining high performance, precision machining of stainless steel force and moment and pressure models, whereby models would be fabricated in days instead of several months. Rapid, precision machining capability exists, is rapidly evolving, and should be routinely available to customers for model fabrication in the relatively near future. Until such time, techniques to construct complex, high fidelity metal-matrix/composite matrix force and moment models amenable for heated flows will continue, along with high temperature resins for SLA. Techniques for ceramic force and moment models will continue to be refined to decrease time of construction and increase fidelity. Models having remotely controlled surfaces will be explored. This technique is commonly used in Langley subsonic to supersonic tunnels, but has not been used in the AFC primarily because of small model size and cost (trade between increased model cost and cost to operate facility). Model support systems will be designed and built for multiple-body separation studies in preparation for Shuttle Orbiter enhancement studies such as liquid flyback boosters and two-stage-to-orbit-concepts. Development and application of a non-intrusive, three-color surface fluorescence technique for simultaneous global measurements of model surface pressure and temperature in heated hypersonic wind tunnels (including the CF_4 tunnel) continues. This technique will extend the temperature range of the presently used phosphor thermography system and provide a smoother model surface via a different coating technique. The subject technique will represent a critical step towards the

ultimate goal of simultaneous force and moment, pressure, and temperature (heat transfer) measurements. This three-color technique will eventually replace the highly successful two-color phosphor thermography technique presently used for essentially all aeroheating studies in the Langley AFC. Until that time, the two-color technique will continue to be improved. Two or three systems will be applied simultaneously to provide multiple views of the model, thereby providing more information faster and reducing the number of tunnel runs required (i.e., cost). Fluorescence techniques will be used during force and moment testing to identify the state of the boundary layer (i.e., laminar, transitional, or turbulent) and locations of flow separation and reattachment often important in the interpretation of force and moment data (e.g., for deflected control surfaces and for wings/fins). Theories/procedures for the extrapolation of phosphor thermography aeroheating measurements to vehicle flight surface temperatures will continue to be developed, calibrated against the rich flight data base for the Shuttle Orbiter and upcoming flight data for X-33 (**Fig. 17**) and X-34, and applied to future aerospace vehicle concepts.

Strides are being taken to more accurately infer heating to thin model surfaces such as fins, tails, wings, and surfaces with small radii of curvature such as leading edges by advances in fluorescence techniques including time response, routine use of 2D/3D conduction codes and/or use of model materials having extremely low thermal conductivity to minimize conduction.

Optical techniques are under development for monitoring model attitude during the run when under pressure and thermal loads. Although the pitch-pause method for force and moment measurements is a tried and proven standard in the Langley AFC, continuous pitch capability may be implemented to substantially increase productivity and reduce thermal effects on the balance. Continuous pitch will require a sufficient increase in strain-gauge balance and data acquisition response, as well as real-time model attitude measurements.

References:

Berry, S. A., Horvath, T. J., DiFulvio, M., Glass, C. E., and Merski, N. R., "X-34 Experimental Aeroheating at Mach 6 and 10," *Journal of Spacecraft and Rockets*, Vol. 36, No. 2, March-April 1999, pp. 171-178.

Berry, S. A., Horvath, T. J., Hollis, B. R., Thompson, R. A., and Hamilton II, H. H., "X-33 Hypersonic Boundary Layer Transition," AIAA Paper 99-3560, June 1999.

Brauckmann, G. J., "X-34 Vehicle Aerodynamic characteristics," *Journal of Spacecraft and Rockets*, Vol. 36, No. 2, March-April 1999, pp. 229-240.

Hamilton II, H. H., Weilmuenster, K. J., Berry, S. A., and Horvath, T. J., "Computational/Experimental Aeroheating Predictions for X-33 Phase II Vehicle," AIAA Paper 98-0869, January 1998.

Hollis, B. R., Horvath, T. J., Berry, S. A., Hamilton II, H. H., and Alter, S. D., "X-33 Computational Aeroheating Predictions and Comparisons with Experimental Data," AIAA Paper 99-3559, June 1999.

Hollis, B. R., Thompson, R. A., Murphy, K. J., Nowak, R. J., Riley, C. J., Wood, W. A., Alter, S. J., and Prabhu, R. K., "X-33 Aerodynamic and Aeroheating Computations for Wind Tunnel and Flight Conditions," AIAA Paper 99-4163, August 1999.

Horvath, T. J., Berry S. A., Hollis, B. R., Liechty, D. S., Hamilton II, H. H., and Merski, N. R., "X-33 Experimental Aeroheating at Mach 6 Using Phosphor Thermography," AIAA Paper 98-3558, June 1999.

Kleb, W. L., Wood, W. A., Gnoffo, P. A., and Alter, S. J., "Computational Aeroheating Predictions for X-34," *Journal of Spacecraft and Rockets*, Vol. 36, No. 2, March-April 1999, pp. 179-188.

Merski, N. R., "Global Aeroheating Wind-Tunnel Measurements Using Improved Two-Color Phosphor Thermography Method," *Journal of Spacecraft and Rockets*, Vol. 36, No. 2, March-April 1999, pp. 160-170.

Micol, J. R., "Langley Aerothermodynamic Facilities Complex: Enhancements and Testing Capabilities," AIAA Paper 98-0147, January 1998.

Miller, C. G., "Aerothermodynamic Flight Simulation Capabilities for Aerospace Vehicles," AIAA Paper 98-2600, June 1998.

Murphy, K. J., Nowak, R. J., Thompson, R. A., Hollis, B. R., and Prabhu, R. K., "X-33 Hypersonic Aerodynamic Characteristics," AIAA Paper 99-4162, August 1999.

Prabhu, R. K., "A Computational Study of an X-33 Configuration at Hypersonic Speeds," NASA/CR-1999-209366, July 1999.

Riley, C. J., Kleb, W. L., and Alter, S. J., "Aeroheating Predictions for X-34 Using an Inviscid Boundary-Layer Method," *Journal of Spacecraft and Rockets*, Vol. 36, No. 2, March-April 1999, pp. 206-215.

Thompson, R. A., Hamilton II, H. H., Berry, S. A., and Horvath, T. J., "Hypersonic Boundary Layer Transition for X-33 Phase II Vehicles," AIAA Paper 98-0867, January 1998.

Wurster, K. E., Riley, C. J., and Zoby, E. V., "Engineering Aerothermal Analysis for X-34 Thermal Protection System Design," *Journal of Spacecraft and Rockets*, Vol. 36, No. 2, March-April 1999, pp. 216-228.

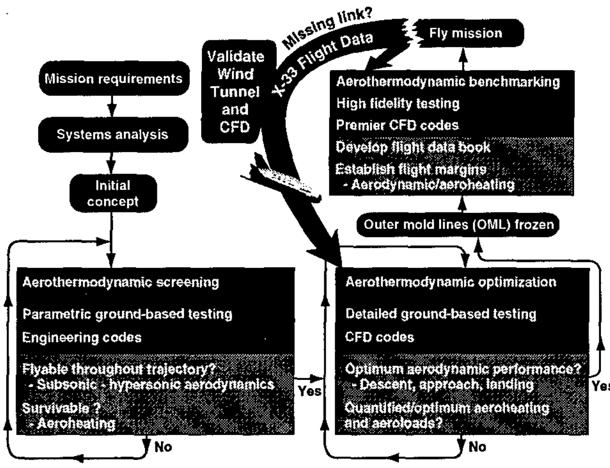


Fig. 1 Aerothermodynamic process.

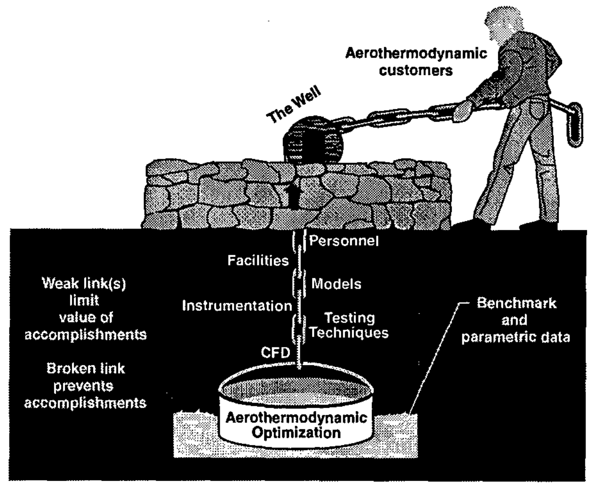
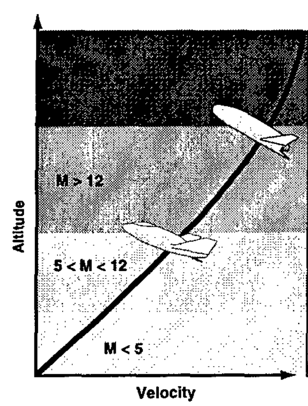


Fig. 4 "Aerothermodynamic chain" representing infrastructure.



Regime	Information Source Primary	Complementary
Rarefied; Free-molecular to near continuum	Direct Simulation Monte Carlo (DSMC)	
Hypervelocity continuum; chemically reacting; "Fully" laminar	CFD	"Specialized" ground-based testing
Hypersonic; laminar/transitional/ turbulent	Ground-based testing	CFD
Supersonic- to-subsonic; "Fully" turbulent	Ground-based testing	CFD

Fig 2. Aerothermodynamic methodology.

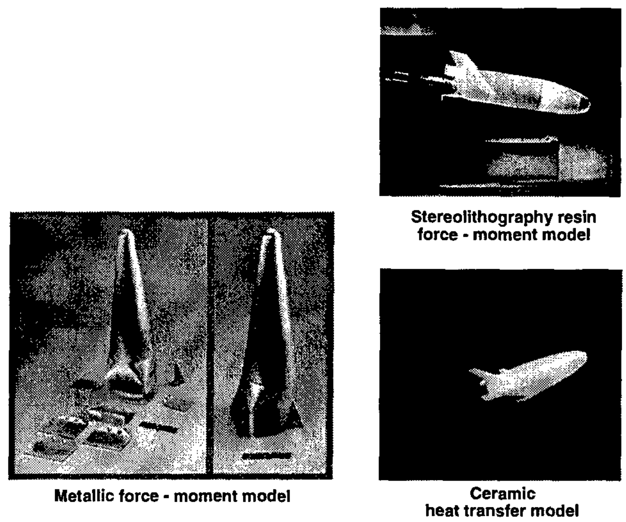


Fig. 5 Representative models for testing in LaRC AFC.

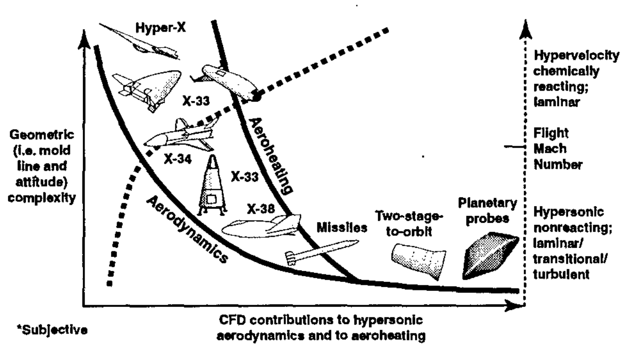


Fig. 3 Relative contribution of CFD.

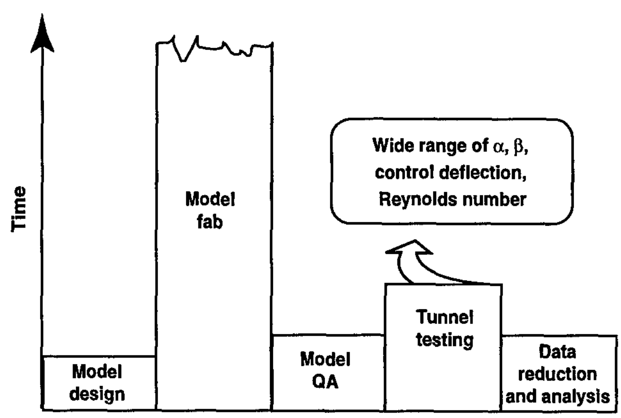


Fig. 6 Relative times associated with typical force and moment study in LaRC AFC.

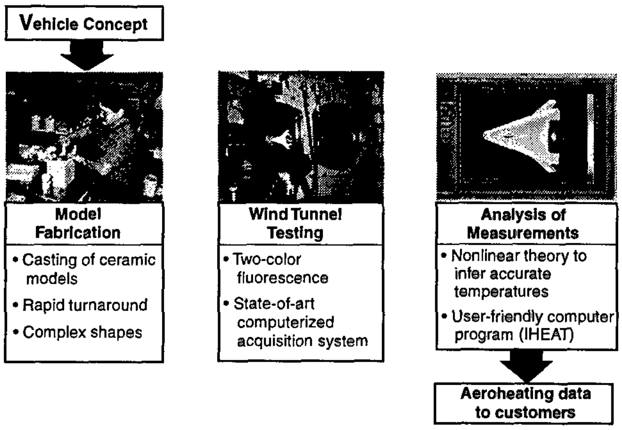


Fig. 7 Phosphor thermography quantitative aeroheating process.

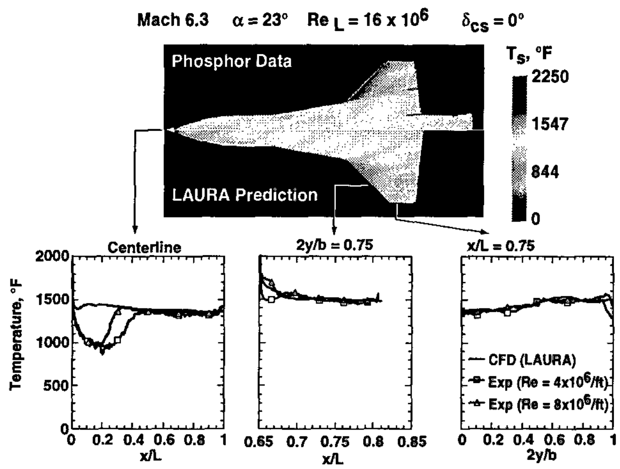


Fig. 8 Extrapolation of X-34 wind tunnel aeroheating measurements to flight; turbulent boundary layer. From Merski et al., 1999.

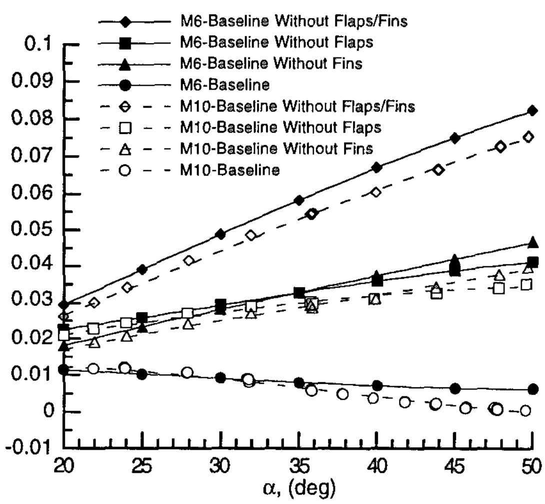


Fig. 9 Measured pitching moment coefficient for X-33 configuration build-up; Mach 6 and 10. From Murphy et al., 1999.

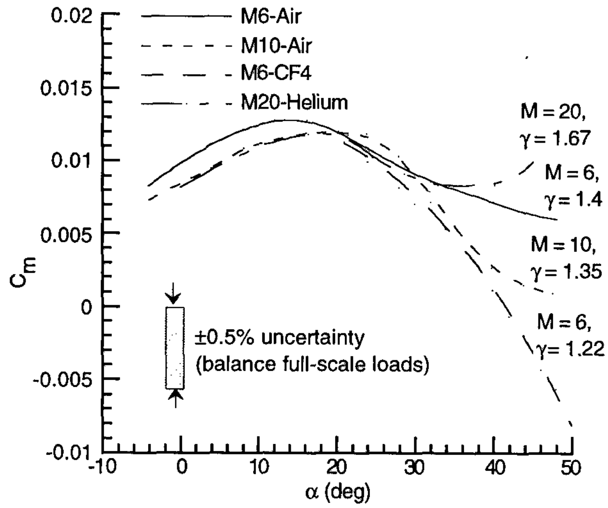
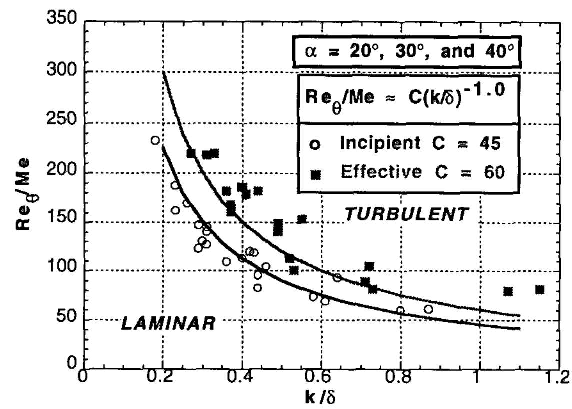
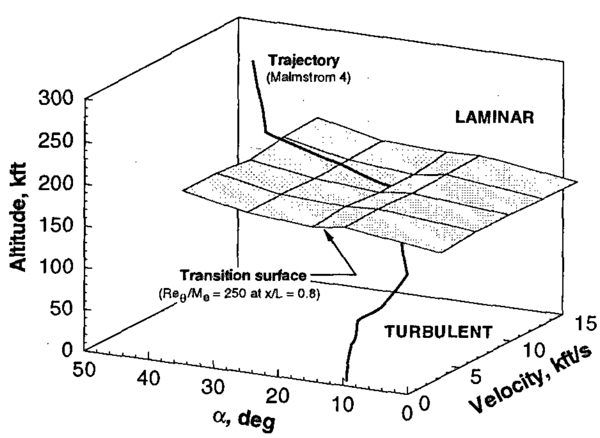


Fig. 10 Effect of Mach Number and shock density ratio on measured pitching moment coefficient for X-33. From Murphy et al., 1999.



(a) Roughness transition correlation. From Berry et al., 1999.

Fig. 11 X-33 boundary layer transition correlation.



(b) Altitude – angle of attack – velocity. From Thompson et al., 1998.

Fig. 11 Concluded.

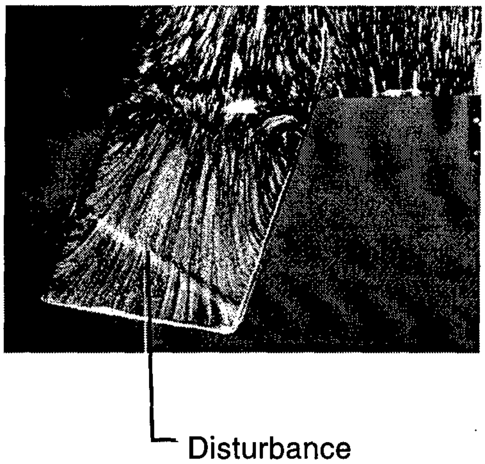


Fig. 12. X-33 body flap surface streamlines. $M_\infty = 6$, $\alpha = 40°$, $\delta_{BF} = 20°$, $Re_\infty = 2 \times 10^6$/ft. From Horvath et al., 1999.

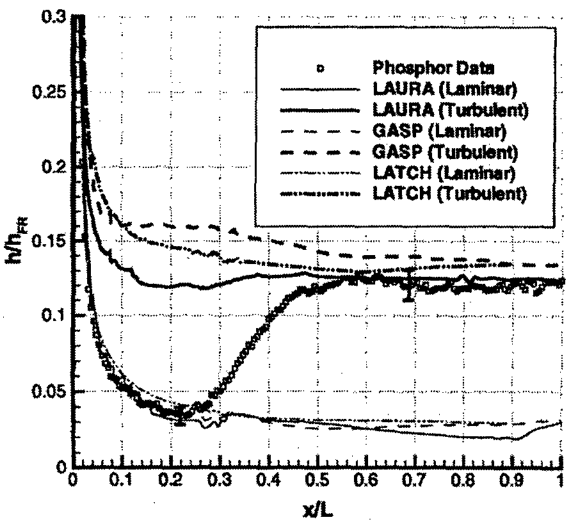


Fig. 13 Phosphor/CFD X-34 centerline comparison. From Merski et al., 1999.

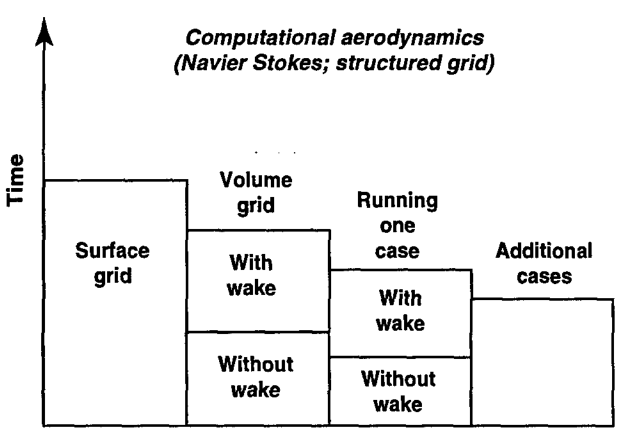
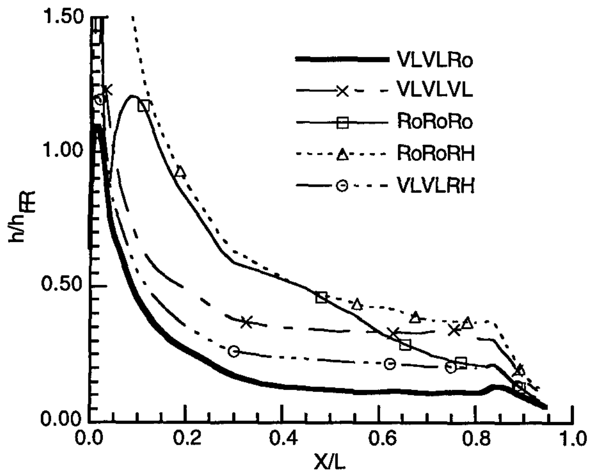
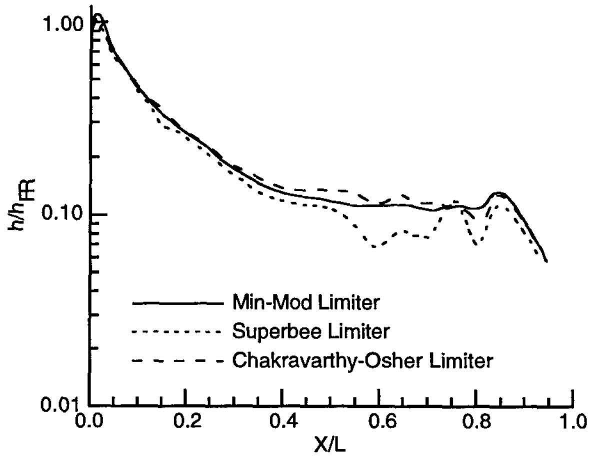


Fig. 14 Relative times associated with typical CFD application.



(a) Flux formulation.

Fig. 15 Effect of flux formulation and TVD limiter on centerline X-33 heating distribution; $\alpha = 40°$ From Hollis et al., 1999.



(b) TVD limiter.

Fig. 15 Concluded.

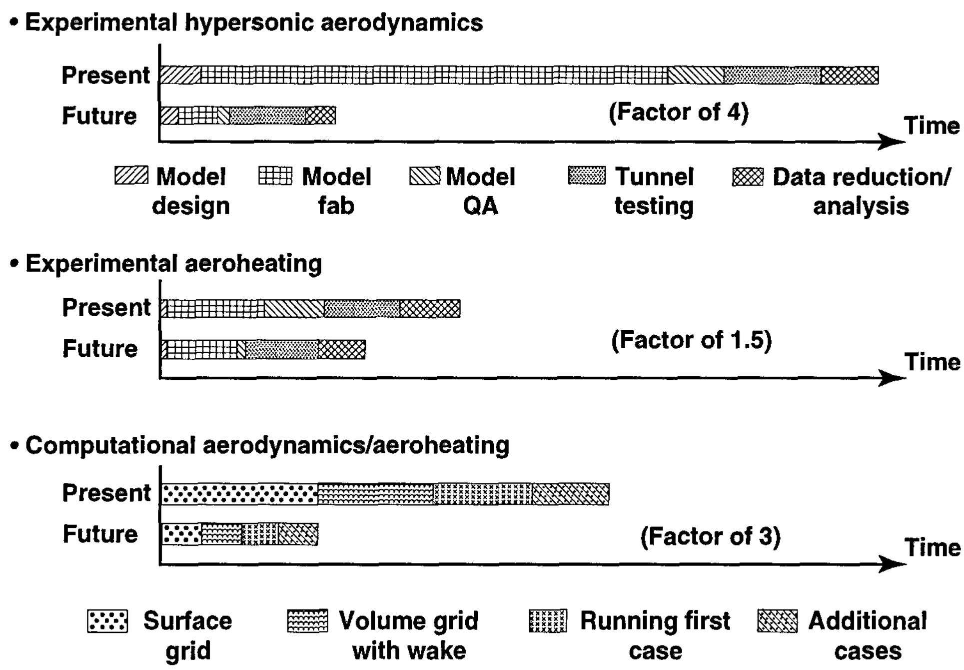


Fig. 16 Aerothermodynamic future goals.

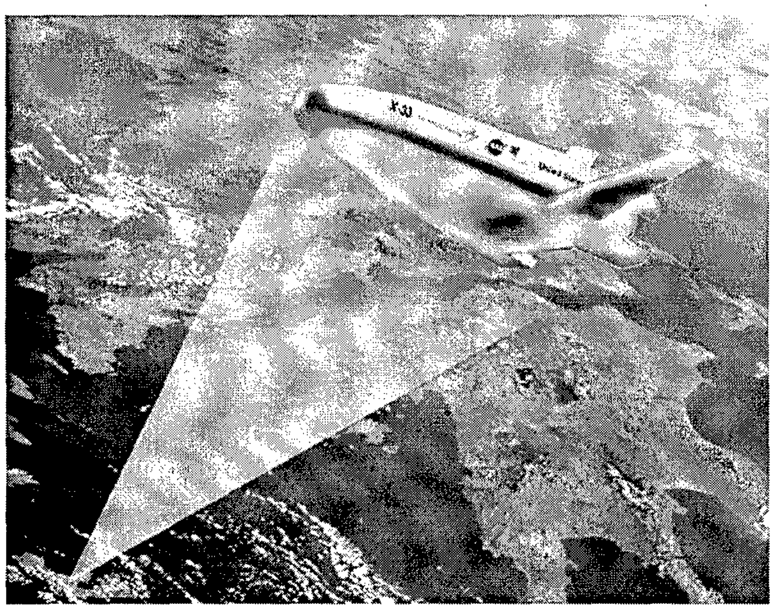


Fig. 17 X-33 flight data extraction and comparison to ground-based data and CFD predictions.